LASER BEAM COUPLING VIA OPTICAL
PHASE CONJUGATION IN $BaTiO_3$

THESIS

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Abstract

The nonlinear crystal barium titanate was used to couple mutually incoherent argon-ion laser beams using a co-pumped four-wave mixing mechanism which transfers photons from each beam into the phase-conjugate outputs of the others. The four-wave mixing geometry which was used has been described in the literature as the "mutually incoherent beam coupler." The beams, all incident on the same crystal a face, form coupling loops as they internally reflect into each other at the opposite crystal corner. Coupling between two and three beams was investigated.

Coupling between two beams resulted in phase-conjugate returns which were both self-pumped and co-pumped. Reflectivities of 9% to 42% were obtained for all angles of incidence greater than 50 degrees. (The angle between beams was less than 7 degrees). The reflectivities were not reproducible. Apparently controlling the crystal orientation to within a half degree and the translational position to within 0.01 mm was not sufficient to guarantee the same beam paths within the crystal. Thus the dependence of the reflectivities on beam angles of incidence and input location could not be quantitatively described.

The reflectivity jumped by 30% when the coupling loop collapsed into two very intense, thin parallel beams running along the loop's inner and outer edges almost all the way back to the entrance face. This preferred state, which has not been reported elsewhere, was not always stable.

The reflectivities for three beam coupling ranged from 1% to 55% . The beams could not be equally coupled; one pair would co-pump the third and vice versa, but co-pumping would not occur in both directions for all three possible beam pairs. Although hysteresis was infrequently observed during two beam mutual co-pumping it was not observed when using three inputs.

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I. Introduction

The Air Force would like to increase the maximum power output of laser systems for use in weapons applications. The desired power is several orders of magnitude greater than that currently available using a single resonator. If a number of separate laser resonators could be phase-locked together their outputs could be coherently combined and the desired power achieved through constructive interference. To attain such coupling it is necessary to inject the output of each independent laser into each of the other lasers. Mutually incoherent beam coupling using optical phase conjugation in the nonlinear crystal barium titanate seems to be an ideal method for doing just that. The phase-conjugate nature of the feedback beams provides mode-matching for each laser cavity, in addition to self-alignment.

To date, beam coupling between two mutually incoherent beams has been demonstrated and used to couple lasers [1-4]. The objective of this thesis was to demonstrate coupling between three incoherent laser beams, to define the parameter space (beam input angles and entrance locations) for which efficient coupling occurs, and to determine the most probable beam coupling mechanisms. In addition, observations of the beam paths within the crystal during co-pumping of the phase-

conjugate output beams were analyzed to gain insight into the beam coupling mechanism.

The approach consisted of three distinct efforts. Self-pumped phase conjugation was demonstrated first to verify the phase-conjugating ability of the crystal sample. Next coupling between two inputs was attempted using the double phase-conjugate mirror configuration, in which the incident beams are almost counter-propagating. This attempt failed, most likely due to an inadequate coupling strength for the crystal sample used. However, two and then three beam coupling were demonstrated using the "mutually incoherent beam coupler" (MIBC), in which the inputs are all incident on the same face of the crystal.

This thesis begins in Chapter II with a review of the fundamental theory governing phase conjugation via four-wave mixing in $BaTiO_3$. Chapter III summarizes some of the pertinent experimental and theoretical work pertaining to the three different conjugating geometries used—the self-pumped phase conjugator, the double phase-conjugate mirror, and the mutually incoherent beam coupler. For completeness a fourth geometry, the bird-wing phase conjugator, is also discussed. Next the equipment and experimental conditions are described. Each of Chapters V, VI, and VII discusses the experimental set-up, observations, and analysis for each of the three geometries. The final chapter summarizes the results and conclusions.

II. Optical Phase Conjugation in $BaTiO_3$

This chapter defines optical phase conjugation and discusses its generation by the nonlinear polarization induced in a medium by the electric fields of three incident laser beams. The holographic analogy to the nonlinear process and the mechanism for producing volume phase holograms through the photorefractive effect are explained.

Optical phase conjugation is a process which exactly reverses both the direction of propagation and the overall phase factor of an incident laser beam. This is mathematically equivalent to taking the complex conjugate of the spatial portion of each of the constituent plane waves of the arbitrary input wave. The result is an output wave whose wavefront is precisely mapped at each point in space to the wavefront which the incident beam had as it propagated (in the opposite direction) through that point in space. The conjugate wave is thus a "time-reversed replica" of the input wave. This property makes it ideal for use in laser coupling; a beam which diverges as it propagates from the laser to the conjugating medium will produce a conjugate beam which converges into the resonator with a matching mode structure. Because the beam automatically "back-tracks" along the incident path there are no alignment considerations.

Nonlinear Generation Via Four-Wave Mixing

The basic geometry of phase conjugation by degenerate four-wave mixing is shown in Figure 1 [5:29]. The inputs consist of two counter-propagating "pump" waves E_1 and E_2, and the probe wave E_p for which the phase conjugate is desired. (Here all of the waves are taken to have the same polarization and the same nominal frequency). Each of the

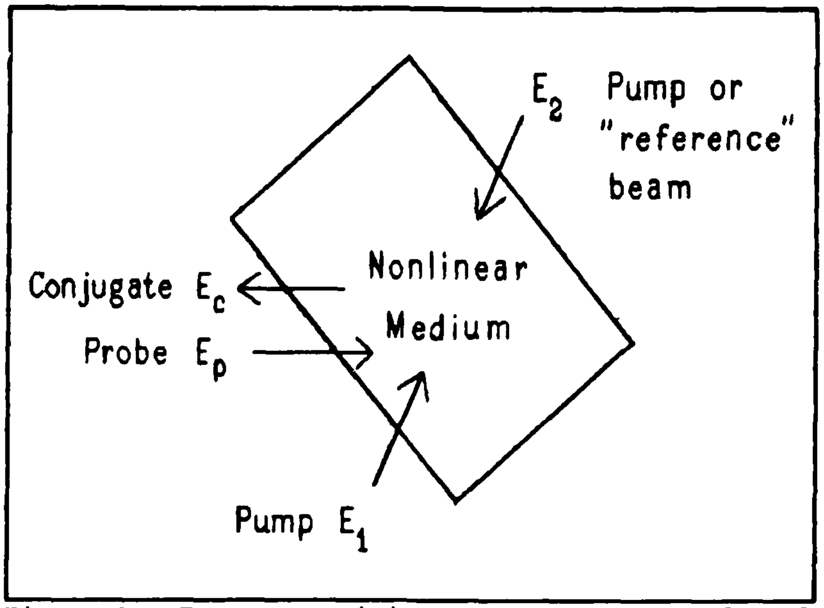

Figure 1. Four-wave mixing geometry. [5,29]

fields produces a nonlinear polarization in the medium which can be expressed in a Taylor series as

$$P_i = \epsilon_o \left\{ \chi^{(1)}_{ij} E_j + \chi^{(2)}_{ijk} E_j E_k + \chi^{(3)}_{ijkl} E_j E_k E_l + \ldots \right\}$$

where P_i is the i^{th} component of the polarization and E_i is the i^{th} component of the electric field. $\chi^{(1)}_{ij}$ is the linear susceptibility, and $\chi^{(2)}_{ijk}$ and $\chi^{(3)}_{ijkl}$ are the second-order and third-order nonlinear susceptibilities [6:504]. It is the term involving the third-order nonlinearity $\chi^{(3)}_{ijkl}$ that results in the generation of the phase-conjugate wave.

The equations governing the interaction of the four waves in the medium have been derived and solved [5:26-36], showing that the nonlinearly generated reflected field is proportional to the complex conjugate of the incident field.

Holographic Representation

There is a formal analogy between the four-wave mixing process discussed above and real-time holography [7:656; 8:164-166]. Consider the conventional procedure for making a thin hologram illustrated in Figure 2.

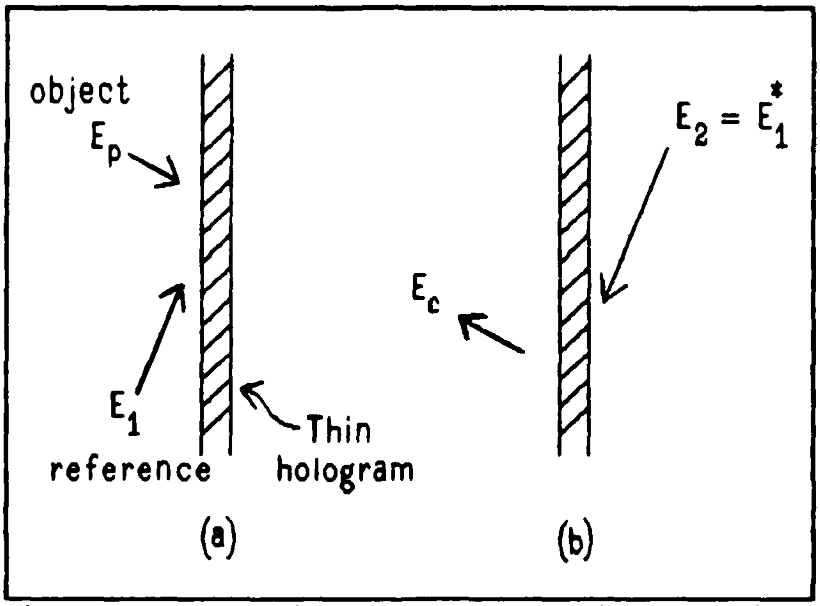

Figure 2. Conventional holography. (a) Recording the hologram. (b) Reading the hologram. [8:64]

The hologram is first recorded using the interference between the planar reference wave E_1 and the object beam E_p. The transmission function is

$$T \; \alpha \; (E_p + E_1)\,(E_p^* + E_1^*) = |E_1|^2 + |E_1|^2 + E_pE_1^* + E_1E_p^*$$

After being developed the hologram is used to reconstruct the object beam by illuminating it with another planar reference beam E_2 propagating opposite to the first. Thus $E_2 = E_1^*$ and the diffracted field

amplitude is

$$\left[\ |E_p|^2 + |E_1|^2\ \right] \cdot E_1^* \quad + \quad |E_1^*|^2\ E_p \quad + \quad |E_1|^2\ E_p^*$$

The last term can be shown to be proportional to the phase conjugate produced through four-wave mixing in the limit of "weak" coupling of the pumps and probe into the phase conjugate, i.e. in the limit of a weak "hologram" [8:165]. Thus four-wave mixing can be thought of as a holographic process which happens in real-time — the recorded hologram needn't be developed before being read out. The phase gratings established by the superposition of the input fields are actually spatial modulations of the nonlinear optical polarization (and thus the index of refraction) in the material.

Phase conjugation can thus be represented as the simultaneous writing and reading of two sets of gratings, as shown in Figure 3.

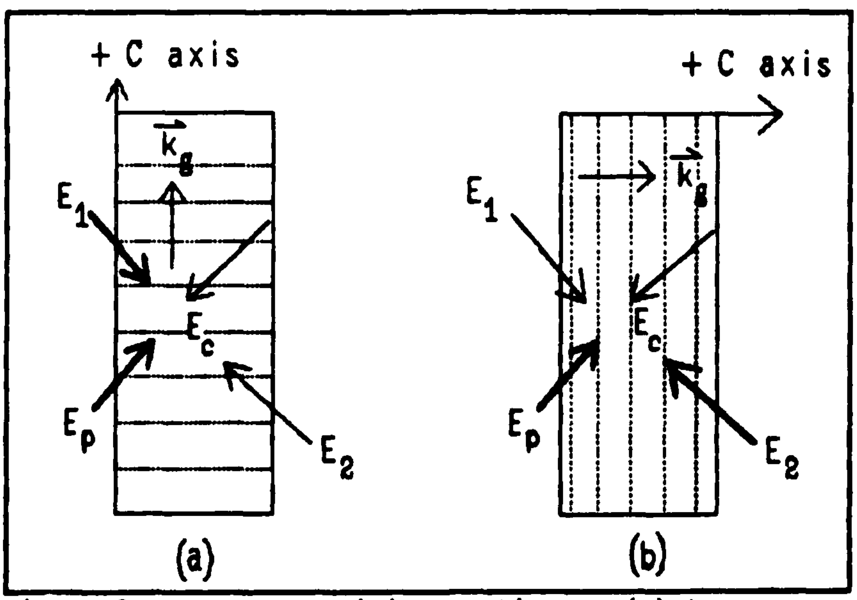

Figure 3. Four-wave mixing gratings: (a) transmission grating (b) reflection grating. The thick arrows denote the writing beams.

Interference between E_p and E_1 writes the larger period grating, from which E_2 Bragg diffracts into the phase-conjugate return E_c. This grating is called a transmission grating because energy incident on one side of the crystal as part of E_2 is transmitted to the other side as part of E_c. The smaller period reflection grating is formed by E_p and E_2. E_1 reads this grating, Bragg diffracting into E_c. Both gratings can contribute to the phase-conjugate return.

It should be emphasized that although the holographic analogy is useful for purposes of discussion, four-wave mixing and holography are not equivalent.

Two classes of nonlinear effects can result in the gratings required for four-wave mixing. The first is the Kerr effect, which involves the response of a material to the local field strength. The second involves the formation of gratings which are spatially shifted from the modulating fields, i.e. they are nonlocal. In $BaTiO_3$ the effect is nonlocal via the photorefractive effect.

The Photorefractive Effect

The photorefractive effect is the change in the refractive index of a crystal due to light-induced migration and separation of charge which gives rise to an electrostatic field [11:417-419]. By the linear electro-optic effect this field produces a rather large refractive index change in materials with large linear electro-optic coefficients, such as $BaTiO_3$. Each index grating is spatially phase shifted by approximately 90° with respect to the interference pattern of the mutually coherent beams which write it.

The steady-state photorefractive index change is independent of the total intensity of the incident beams, depending only on their relative intensity. This can be explained as follows. The light intensity pattern produced by the interference of the writing beams $\vec{E}_p$ and $\vec{E}_2$ within the crystal is given by $I(\vec{x}) = I_o \cdot (1 + m \cos(\vec{k} \cdot \vec{x}))$ where $I_o = |\vec{E}_p|^2 + |\vec{E}_1|^2$, $m = 2 \cdot (\vec{E}_p \cdot \vec{E}_1) / I_o$, $\vec{k} = \vec{k}_p - \vec{k}_1$, and $\vec{x}$ specifies an arbitrary direction within the crystal. The modulation index m is a measure of the visibility of the fringes. For writing beams of equal intensity m = 1; when one beam is much weaker than the other m « 1. The visibility of these interference fringes determines the magnitude of the static electric field E generated by the re-distribution of charge to low intensity regions [11; 420-424]. Thus, since E is proportional to m, the modulation in the refractive index will be dependent only on the relative intensity of the writing beams. However, the speed of the photorefractive effect increases as the intensity is increased [11:418].

The Grating Coupling Constant γ

The relative coupling strength of each of the possible gratings is given by $\gamma \ell$ where γ is a coupling constant and ℓ is the effective length of the beam interaction. In $BaTiO_3$ γ is calculated using [9; 12]:

$$\gamma = \frac{\pi E\, n_o^3\, r_{eff}}{2\lambda_o \cos\theta},$$

with the variables defined below and in Figure 4.

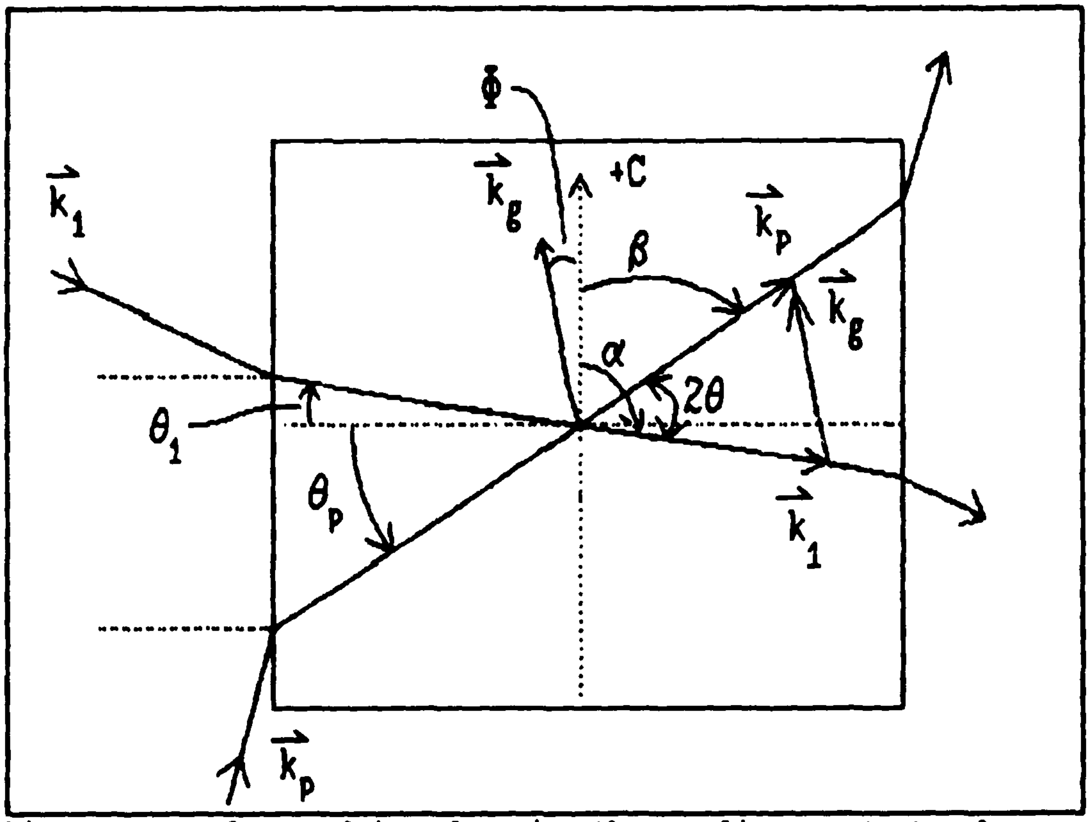

Figure 4. Angles used in calcuating the coupling constant γ for the grating formed by E_1 and E_p.

n_o, n_e = the refractive indices for ordinary and extraordinary rays

λ_o = the wavelength in free space

$\theta = \dfrac{\alpha - \beta}{2}$ = the half angle between the writing beams.

α = the angle between the grating wave vector $\vec{k}_g$ and the +C axis

β = the angle between $\vec{k}_g$ and the +C axis

(α and β positive when taken clockwise from the +C axis.)

$k_g = |\vec{k}_g| = |\vec{k}_p - \vec{k}_1| = 2k \sin\theta$ = the grating wave vector.

(Note that this equation for k_g is derived by neglecting the different values of n_e for beams propagating in different directions; $n_e(\alpha)$ is taken to be equal to $n_e(\beta) = n_e$ so that $|\vec{k}_p| \approx |\vec{k}_1| \equiv k \equiv 2\pi n_e/\lambda_o$).

$$E = \frac{k_B\ T}{q} \cdot \frac{k_g}{1 + \left(\frac{k_g}{k_o}\right)^2}$$ = the magnitude of the steady-state field produced by the separation of charge.

q = electronic charge = + 1.602 $\times 10^{19}$ C

k_B = Boltzmann's constant = 1.38 $\times 10^{-23}$ J/K

T = temperature in Kelvin

k_o is the inverse Debye screening length, a crystal parameter given by:

$$\frac{1}{k_o^2} = \frac{\epsilon_o \epsilon_{DC}(\phi)\ k_B T}{q^2\ N_d},$$

where ϵ_o = 8.85 $\times 10^{-12}$ F/m = the permittivity of free space,

ϕ = the angle between the +C axis and the k_g vector,

$$\epsilon_{DC}(\phi) = \epsilon_{\parallel} \cos^2 \phi + \epsilon_{\perp} \sin^2 \phi$$ = the effective dielectric constant in the grating direction

$\epsilon_{\parallel}$ = the dielectric constant for an E field parallel to the +C axis

$\epsilon_{\perp}$ = the dielectric constant for an E field perpendicular to the +C axis

N_d = (1.9 to 8.7) $\times 10^{16}$ cm^{-3} = the number density of charge carriers available for migration [13:4903; 14].

The effective electro-optic coefficients for each type of wave are given by:

$$r^{o}_{eff} = r_{13}\sin\left[\frac{\alpha+\beta}{2}\right] = r_{13}\cos\phi \qquad \text{for ordinary waves, and}$$

$$r^{e}_{eff} = \frac{\sin\left[\frac{\alpha-\beta}{2}\right]}{n_o n_e^3}\cdot\left\{ n_e^4 r_{13}\cos\alpha\cos\beta + 2n_o^2 n_e^2 r_{42}\cos^2\left[\frac{\alpha+\beta}{2}\right] + n_e^4 r_{33}\sin\alpha\sin\beta \right\}$$

for extraordinary waves. Alternatively, r^{e}_{eff} can be expressed in terms of θ and ϕ as:

$$r^{e}_{eff} = \frac{\cos\phi}{2n_e n_o^3}\left\{ n_o^4\, r_{13}(\cos 2\theta - \cos 2\phi) + 4n_o^2 n_e^2\, r_{42}\sin^2\phi + n_e^4\, r_{33}(\cos 2\theta + \cos 2\phi) \right\}$$

For $BaTiO_3$ the crystal constants are $n_o = 2.488$, $n_e = 2.424$ [15:1800], $\epsilon_{\parallel} = 168$, $\epsilon_{\perp} = 4300$ [16:350; 17; 13], and $r_{13} = 24$, $r_{33} = 80$, $r_{42} = 1640$ (unclamped values in pm/V) [12:223; 13]. Note that $\gamma(\theta) = -\gamma(180° - \theta)$ and $\gamma(\phi) = \gamma(-\phi) = -\gamma(180° - \phi)$. The coupling constant γ as a function of ϕ (the angle between the grating wave vector $\vec{k}_g$ and the +C axis) is graphed in Figure 5 for a number of different beam-crossing half-angles θ in a crystal with $N_d = 3.0 \times 10^{16}$ charge carriers/cm^3. γ is greater for small θ and intermediate ϕ. Thus the predominance of one grating can be enhanced (in order to prevent competition among the gratings and a resulting drop in the conjugate

reflectivity) by the choice of directions and coherence relationships of the four beams relative to the crystal axes. As long as the beam crossing angle is small enough that $\vec{k}_g$ is well separated in direction from the grating wave vectors formed by the other pairs of beams, the crystal can be oriented so that $\vec{k}_g$ will be the only effective grating [18:549]. Then only a single phase conjugate output beam will be produced.

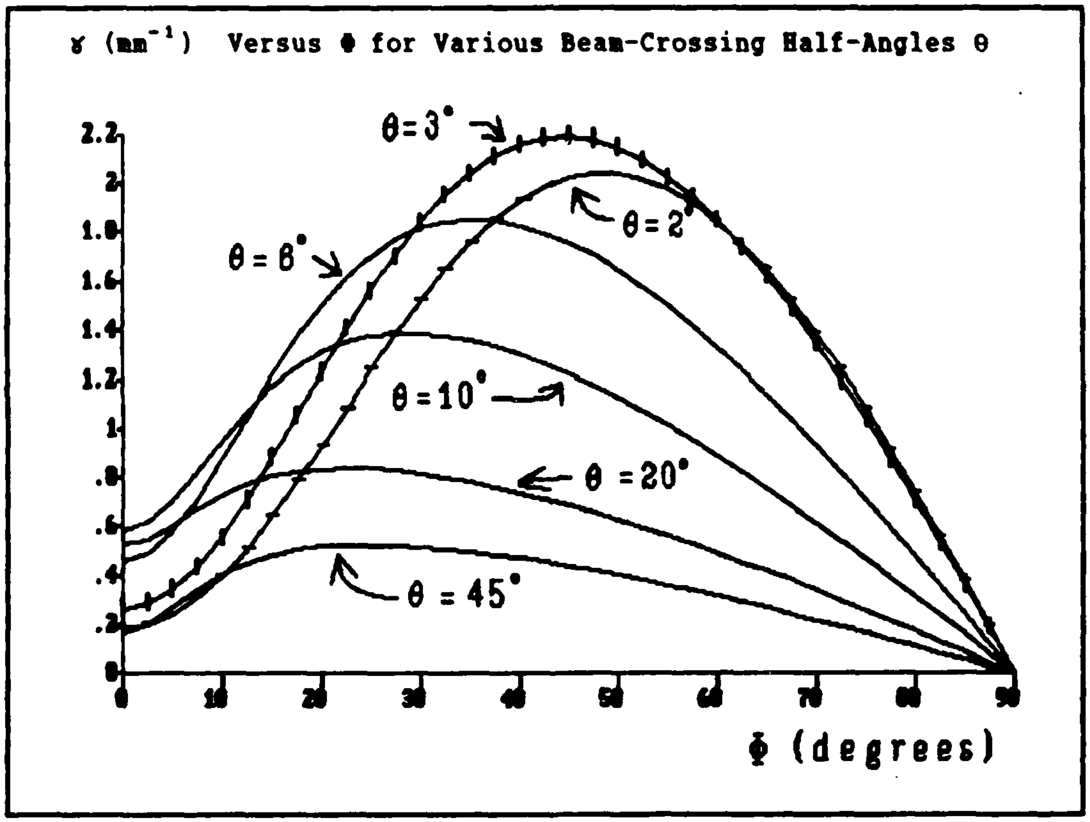

Figure 5. γ as a function of Φ for various angles θ.

III. Optical Phase Conjugation Geometries

Self-Pumped Phase Conjugation

Optical phase conjugation via four-wave mixing in $BaTiO_3$ is most easily achieved using a self-pumped geometry in which the incident probe beam generates its own pumping beams within the crystal. Externally applied pump beams are not required. This self-pumping is made possible by two photorefractive effects discussed below: beam fanning and two-wave mixing.

An extraordinarily polarized beam incident on a $BaTiO_3$ crystal at an angle to the +C axis will "fan out" within the crystal toward the +C face, as illustrated in Figure 6. This fanning is due to the linear change in refractive index produced by the Gaussian beam, as shown in Figure 7. Fanning gratings are formed as different parts of

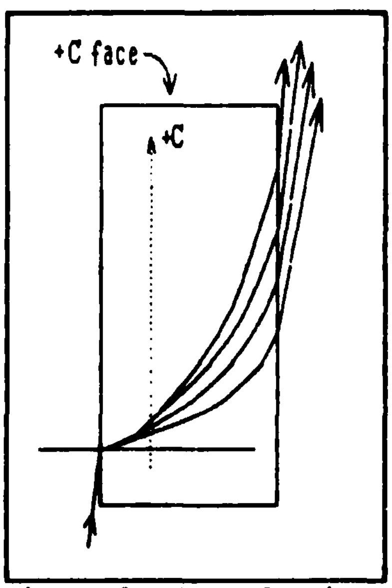

Figure 6. Beam fanning of an extraordinary wave Gaussian beam.

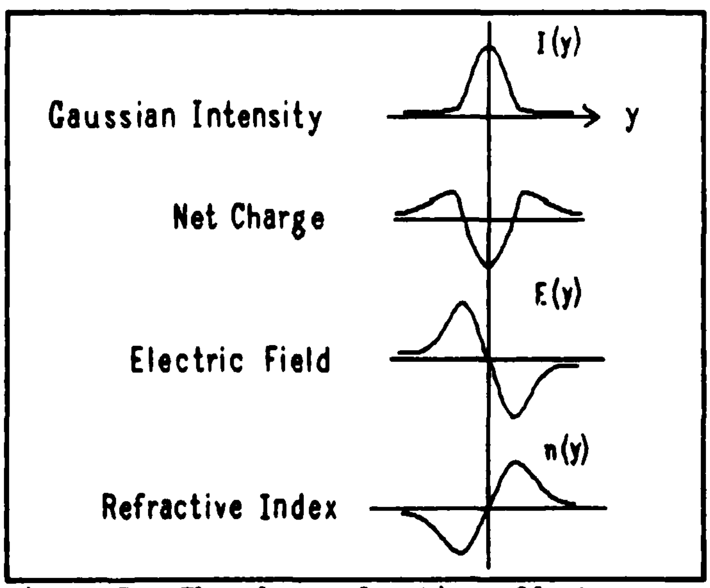

Figure 7. The photorefractive effect causes the refractive index variation which results in beam fanning. [19:48]

the original beam interfere as they propagate through the crystal.

Two-wave mixing (also referred to as two-beam coupling) is a process in which energy can be transferred between two beams as they scatter off the very grating which they create [20:822]. The 90° phase shift between the index grating and the light interference pattern shifts the grating toward one beam and away from the other, allowing one beam to accept and the other to donate energy. The beam propagating toward the +C face is amplified at the expense of the other.

The strength of fanning and beam coupling for different orientations of the crystal's +C axis with respect to the beams is again determined using the coupling constant γ. Together fanning and two-beam coupling allow a stable self-pumped geometry to form as follows.

The angle of incidence and the orientation of the crystal are chosen such that the input beam will fan toward the +C crystal face and be internally reflected at a crystal corner as shown in Figure 8.

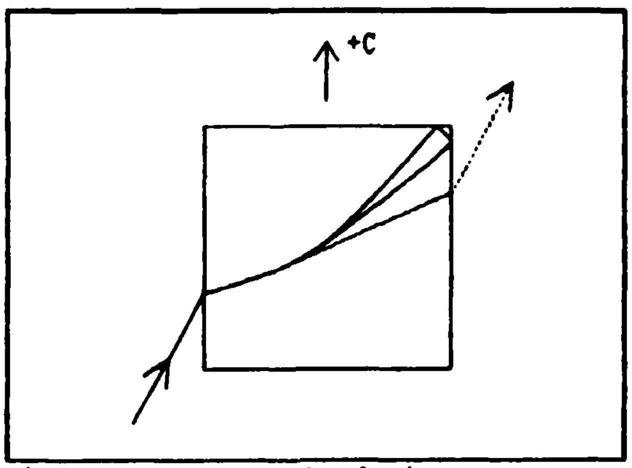

Figure 8. Beam paths during self-pumping.

Counter-propagating loops of light form when one portion of the input beam is reflected before fanning past the corner and another portion is reflected after fanning past the corner. After the grating has been formed the incident beam is diffracted directly into the loop (rather than being fanned), reinforcing the grating. Two-wave mixing into the fanned direction from the incident beam increases the strength of the pump beams within the loop.

Gower and Hribek have postulated that reflection gratings are created by the counter-propagating beams within each half of the loop, reflecting the collinear probe beam into its phase conjugate [21:1752]. Other theories describe the self-pumping mechanism in terms of two separate but coupled (non-collinear) four-wave mixing interaction regions [18], in terms of stimulated parametric scattering [22:909], or in terms of stimulated two-wave mixing [17:214; 23:85].

Although the mechanisms underlying self-pumped phase conjugation have not been fully resolved there is greater agreement on the experimentally observed behavior of the self-pumped output. The Gower and Hribek paper details their comprehensive study of the effect of beam entrance location, beam intensity, beam power, beam diameter, and crystal dimensions on the nature of the phase-conjugate return. The beam entrance location in particular determines whether the return will exhibit frequency shifts, pulsations, or oscillations. The determining factor appears to be the efficiency with which light can couple into a four-wave mixing loop using only one crystal corner. Their results indicate that although the nature of the phase-conjugate reflectivity can be theoretically explained based on the observed beam paths within a

given crystal, it cannot be easily generalized to predict the behavior for different crystal samples.

<u>Mutually Pumped Multiple Beam Conjugation</u>

Mutually pumped phase conjugation refers to the process in which two or more laser beams are used to pump each other's phase-conjugate output beams through a cross-readout process [24:1743]. The photons in each conjugate originate from one or more of the other beams. These beams pump the phase-conjugate output. The input beams may be mutually coherent or incoherent, although coherent beams may cause unstable reflectivities due to the competing photorefractive gratings formed. Each phase conjugate is mutually coherent with the beams which pump it. Thus, although each input-output pair are phase conjugates, they may not be mutually coherent. Phase-conjugate output is possible even without an exact frequency matching of the lasers as long as the frequency difference is small enough that the volume gratings' selectivity still allows Bragg scattering [2:528]. The spatial wavefront of each input is reconstructed without crosstalk between the beams, but the frequencies are exchanged and sometimes modified [24:1745].

The three configurations shown in Figure 9 have been shown to produce mutually pumped phase conjugation between two input beams. The main difference between the geometries is the number of internal reflections within the $BaTiO_3$ crystal: none for the double phase-conjugate mirror, one for the bird-wing phase conjugator, and two for the mutually incoherent beam coupler. The mechanism for four-wave mixing in each geometry, as described by the investigators who first demonstrated them, are given below.

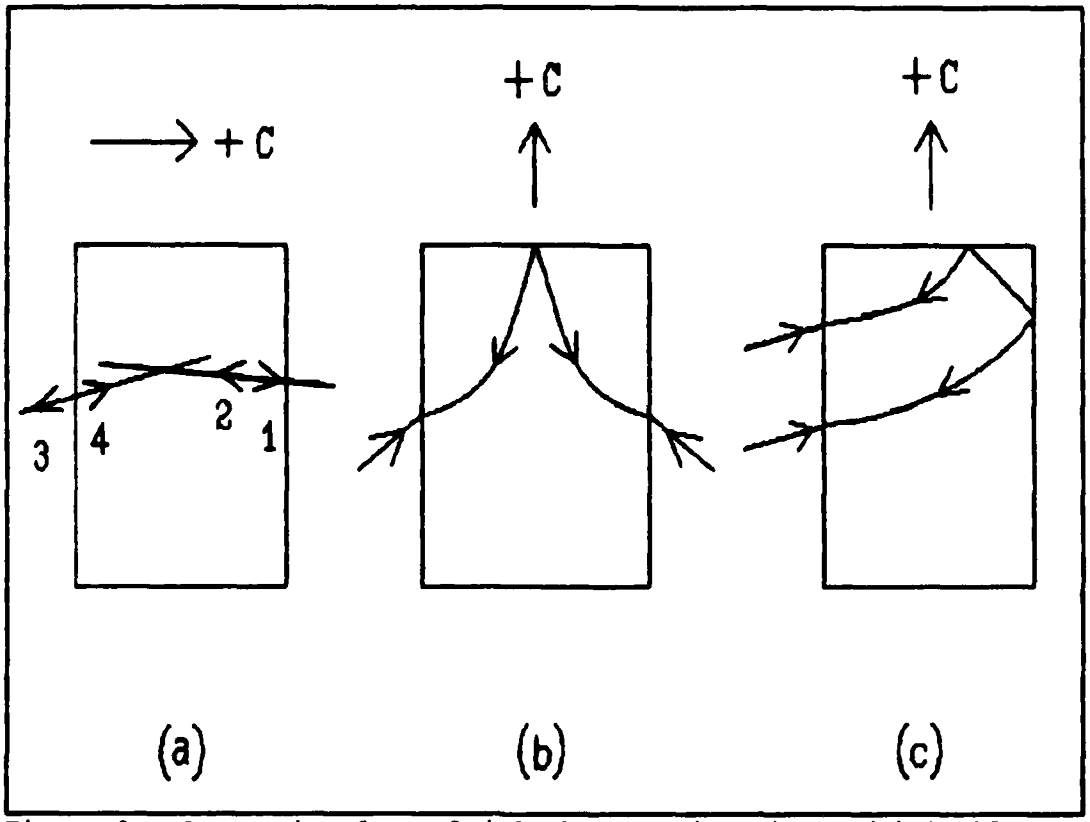

Figure 9. Geometries for multiple beam conjugation. (a) Double phase-conjugate mirror. (b) Bird-wing conjugator. (c) Mutually incoherent beam coupler.

<u>The Double Phase-Conjugate Mirror</u>. The double phase-conjugate mirror conjugates two beams incident on the crystal from opposite sides. The crystal is oriented as shown in Figure 9. Initially beam 4 fans into the 1 direction. Self-induced transmission gratings are then written by beams 4 and 1, causing beam 2 to scatter into beam 3. Beams 2, 3, and 4 then produce the four-wave mixing that generates beam 1. Thus beams 1 and 2 pump $E_3 = E_4^*$ and beams 3 and 4 pump $E_1 = E_2^*$.

Although the double phase-conjugate mirror has been demonstrated experimentally [25] there is still some question concerning the validity of the phase-conjugate return as they described it. In order for the

output beams to be the phase conjugates of the input beams the pumping beams for each four-wave mixing process have to be phase conjugates. Cronin-Golomb et. al. [9] showed experimentally and theoretically that without feedback of the pumping beams 1 and 3 back into the crystal phase-conjugate oscillations will not have an advantage over other kinds of oscillation. These other kinds of oscillations arise due to the fact that both beams 1 and 3 are self-generated in the crystal, rather than just beam 3 as in externally pumped four-wave mixing [9:24; 26:711].

We require that $\vec{k}_g = \vec{k}_4 - \vec{k}_1 = \vec{k}_2 - \vec{k}_3$ in order to form a single grating which couples all four beams. If only $\vec{k}_2$ and $\vec{k}_4$ are fixed externally the extra degree of freedom allows beams 1 and 3 to appear as cones of light with axes $\vec{k}_4 - \vec{k}_2$ and surfaces including $\vec{k}_2$ and $\vec{k}_4$. Thus only a small portion of the output will be in the phase-conjugate direction.

In the double phase-conjugate mirror there presumably is no feedback but high quality phase conjugation has been demonstrated. Apparently, in this case, in contrast to the case tested in [9], the fact that production of counter-propagating conjugate pairs results in maximum overlap of the beams is enough to give the conjugate oscillations an advantage even without feedback. The gratings which generate the conjugate return are stronger than the gratings which generate the conical diffraction. Sternklar and Fisher [26:712] have reported that spatially modulated (image-bearing) inputs improve the conjugation quality of the double phase-conjugate mirror. The oscillation vectors $\vec{k}_1$ and $\vec{k}_3$ must then satisfy both the overlap and Bragg conditions for

each spatial frequency of the inputs, eliminating the conical diffraction and improving the fidelity of the phase-conjugate return.

The Bird-Wing Phase Conjugator. In the bird-wing conjugator the beams are again incident on opposite sides of the crystal, but in this case the +C axis is oriented such that both beams fan symmetrically toward it. (See Figure 9). There they are internally reflected into the opposite input beam, Bragg diffracting off its fanning gratings to produce the phase-conjugate return. Ewbank explains the advantage in gain which conjugate oscillations possess as follows:

> The fanning holograms generated from one incident beam will reinforce the fanning holograms produced by the second incident beam only if the light diffracted from the first incident beam's hologram is the phase conjugate of the diffracted light from the second beam. That is, all photorefractive fanning holograms produced independently by the two incident beams will wash out unless they are written by phase-conjugated beams [27:48].

This explanation is consistent with that given for the double phase-conjugate mirror and applies for any of the multiple beam couplers.

Because of the crystal's orientation, competition exists between the co-pumped bird-wing conjugator and independent self-pumping of the inputs. The bird-wing gratings will dominate if the incident beams are configured to minimize self-pumping or if the intensities are balanced such that self-pumping gratings are erased by the other beam.

The Mutually Incoherent Beam Coupler. The crystal orientation used in the mutually incoherent beam coupler is similar to that used in the bird-wing conjugator, except that both beams are incident from one side. Each beams fans toward the +C face and is internally reflected

near the corner such that it is approximately counter-propagating to the other beam. (See Figure 9). Provided that the Bragg conditions are satisfied, light from each beam scatters off the other beam's fanning gratings and the phase-conjugate beams are generated. The mutually consistent gratings are self-reinforcing, with the result that the fanned light condenses into a loop [28].

Currently the accepted explanation of the phase conjugating mechanism involves the formation of two distinct four-wave mixing interaction regions within the crystal as shown in Figure 10(a). Alternatively, Gower recently proposed a four-wave mixing mechanism in which a closed ring of light (rather than an open loop) provides the internally reflected pumping beams. This is illustrated in Figure 10(b). The top part of the ring (near the +C face) is more intense than the bottom part since two-wave mixing amplifies the beams propagating in that direction. Experimentally it has been demonstrated that the mutually incoherent beam coupler reflectivity exhibits strong bistability and hysteresis as a function of the intensity ratio between the two inputs, although the reason this occurs is not clear.

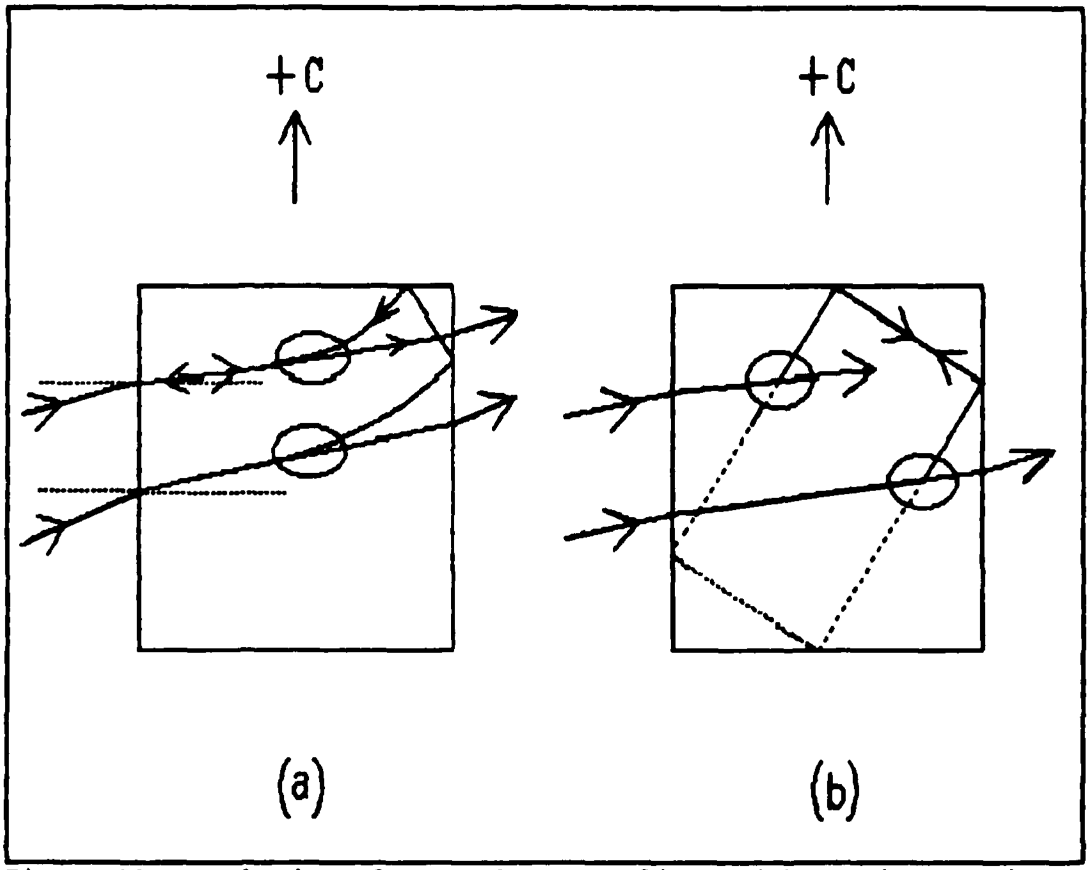

Figure 10. Mechanisms for two beam coupling. (a) two interaction regions (b) two interaction regions using a ring cavity [24; 28].

IV. Equipment and Experimental Conditions

Two argon-ion lasers were used in this experiment: a Spectra-Physics Model 162A and an Ion Laser Technology Model 5490 AWC. Both were operated in the light power control mode using the 514.5 nm green line. These lasers emit nominally vertically polarized light. Half wave plates were used to rotate the polarizations to horizontal so that the beam would be an extraordinary wave within a crystal with its +C axis in the horizontal plane. Optical powers were measured using EG&G Model 450 radiometers and recorded using a y-t strip chart recorder.

The crystal was approximately 6.0 mm x 5.5 mm x 4.0 mm, with the +C axis parallel to the 6.0 mm side. It was placed on a rotating/translating stage so that the direction of the +C axis and the beam entrance locations could be easily varied. Phase-conjugate reflectivities were measured in the dark in order to prevent ambient light from decreasing the index modulation within the crystal. The effects of conjugate feedback on the laser's stability were checked periodically by monitoring the laser output intensity. No effect was observed.

V. Self-Pumped Phase Conjugation

Self-pumped phase conjugation was demonstrated first to verify that the crystal was strong enough to produce a phase-conjugate output at the power levels available. Self-pumping was easily achieved for both image-bearing and Gaussian input beams, with and without a phase aberrator (a piece of acid-etched glass) in the beam path. The experimental set-up used to produce the self-pumped phase conjugate of an image bearing beam is shown in Figure 11.

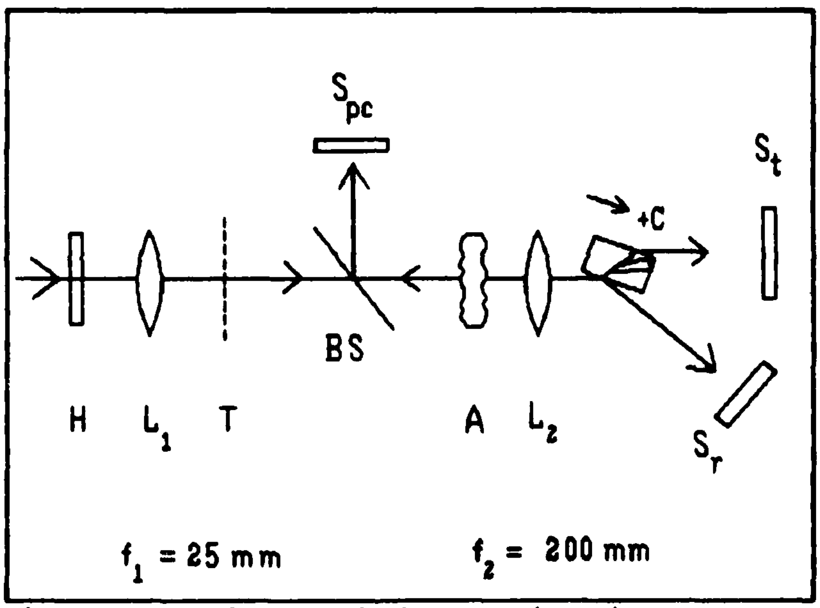

Figure 11. Self-pumped phase conjugation set-up. The elements are: H: half-wave plate; L: lenses; T: Air Force chart; BS: beam splitter; A: phase aberrator; and S: screens.

Screens S_r and S_{pc} were used to compare the phase-conjugate image to the incident image. Steady-state reflectivities were reached within 1 min-

ute, with a visible return appearing after approximately 15 seconds for a 5.5 mW/cm² input beam. With or without the aberrator 11.3 lines/mm on the chart were resolved. (The etched glass aberrated the beam such that the reflected chart was unrecognizable). See Figure 12.

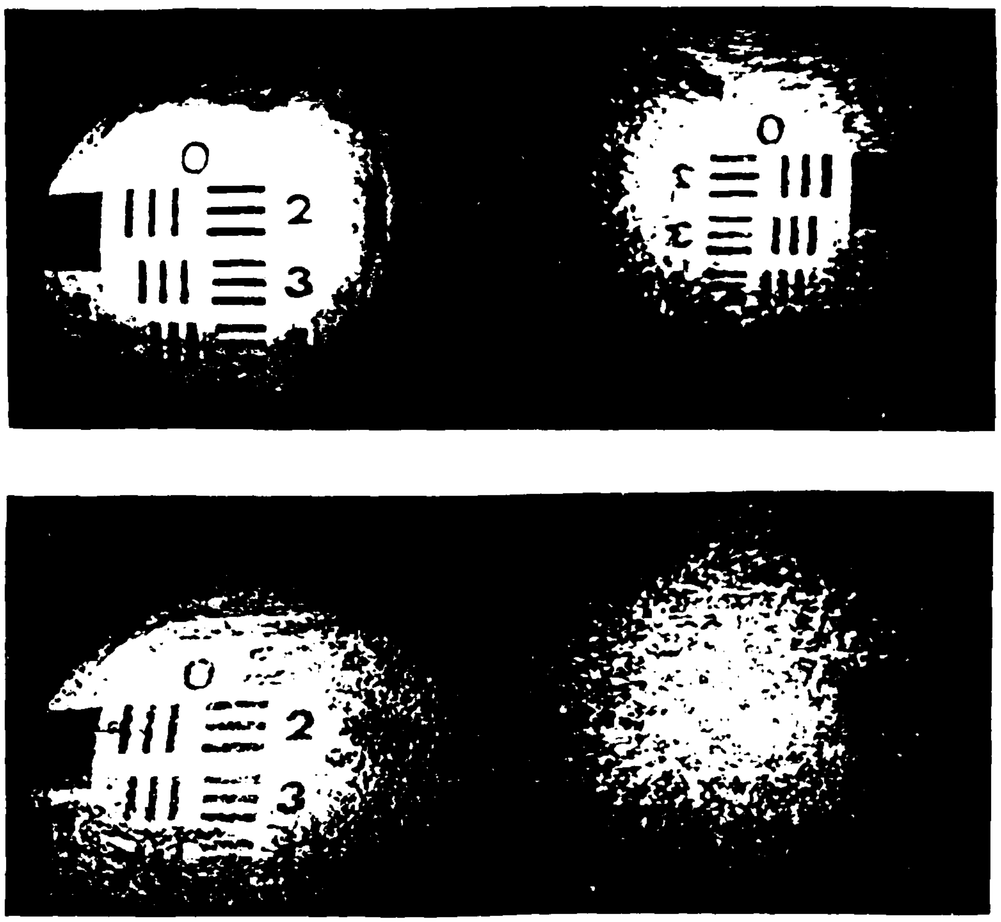

Figure 12. Comparison of the self-pumped phase-conjugate output beam (left) and the image-bearing input beam as reflected from the first crystal face (right). Top: unaberrated input. Bottom: aberrated input.

Portions of the transmitted beam at screen S_t darkened as the phase-conjugate reflectivity increased.

The phase-conjugate reflectivity of a Gaussian input beam as a function of input angle was then measured using a collimated beam approximately 1 mm in diameter. The beam entrance location was optimized for a 40° angle of incidence by observing the speed and magnitude of the response on a strip chart as the crystal was translated across the beam. The maximum reflectivity occurred for beam entrances approximately 1 to 2 mm from the +C face of the crystal, as expected [21]. The reflectivity measurements were then made using the set-up shown in Figure 13.

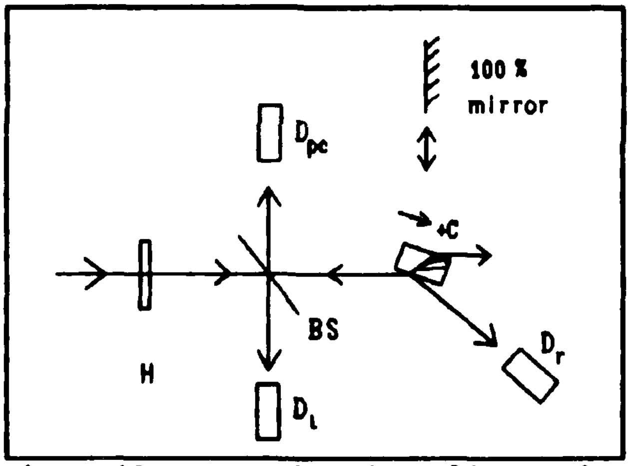

Figure 13. Measuring the self-pumped phase conjugate reflectivity. H: half-wave plate; BS: beam splitter; D_L, D_{PC}, D_r: detectors.

The reflectivities, both corrected and uncorrected for Fresnel reflections at the crystal face, are graphed in Figure 14. The phase-conjugate return appeared to grow in time as a saturating exponential.

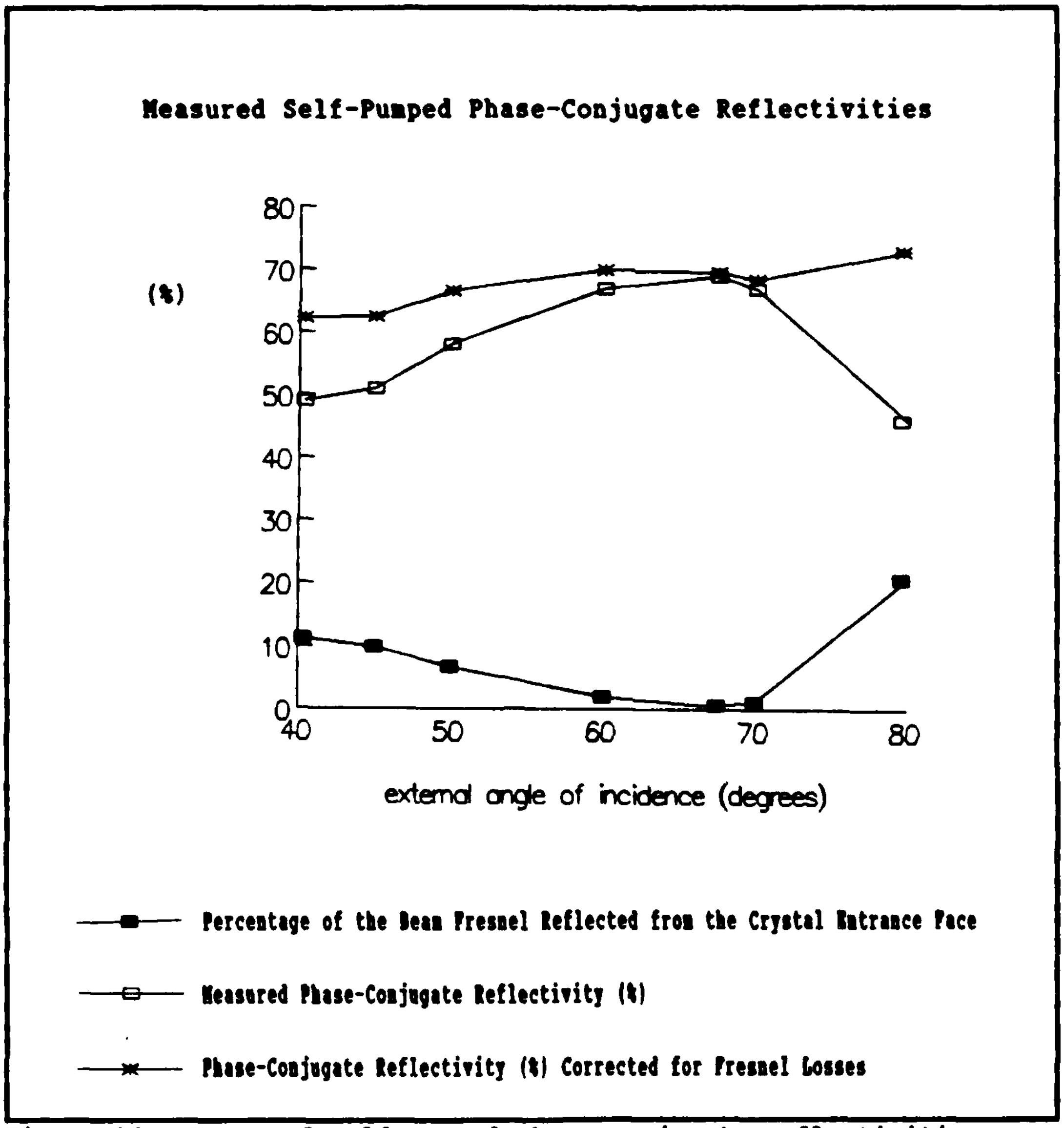

Figure 14. Measured self-pumped phase-conjugate reflectivities as a function of the external angle of incidence of the Gaussian input beam.

After reaching steady-state, the conjugate intensity fluctuated approximately 5% below its average and 1% above its average. The laser output, which was monitored using detector D_L, was not affected by the phase-conjugate feedback.

The high reflectivities indicate that this crystal has a relatively large number density N_D of charge carriers available for migration. (In the literature reflectivities from 30 to 50% have been reported). It must be emphasized, however, that although self-pumped phase-conjugate emission was easily obtained in almost all instances and for many angles (including angles less than 40°), the measured reflectivity varied widely depending on the position of the incident beam on the entrance face. Just changing the height of the beam reduced the maximum phase-conjugate reflectivity to 40% from 69%. Thus, although the trend shown in Figure 14 can be reproduced, the values shown can only be obtained only after optimizing the beam entrance location as described previously. Apparently the distribution of charge carriers /scattering defects is not uniform within the crystal.

VI. The Double Phase-Conjugate Mirror

The double phase-conjugate mirror configuration shown in Figure 15 was set up in an attempt to reproduce the results of Weiss, Sternklar, and Fischer [25]. The path difference between beams 2 and 4 was

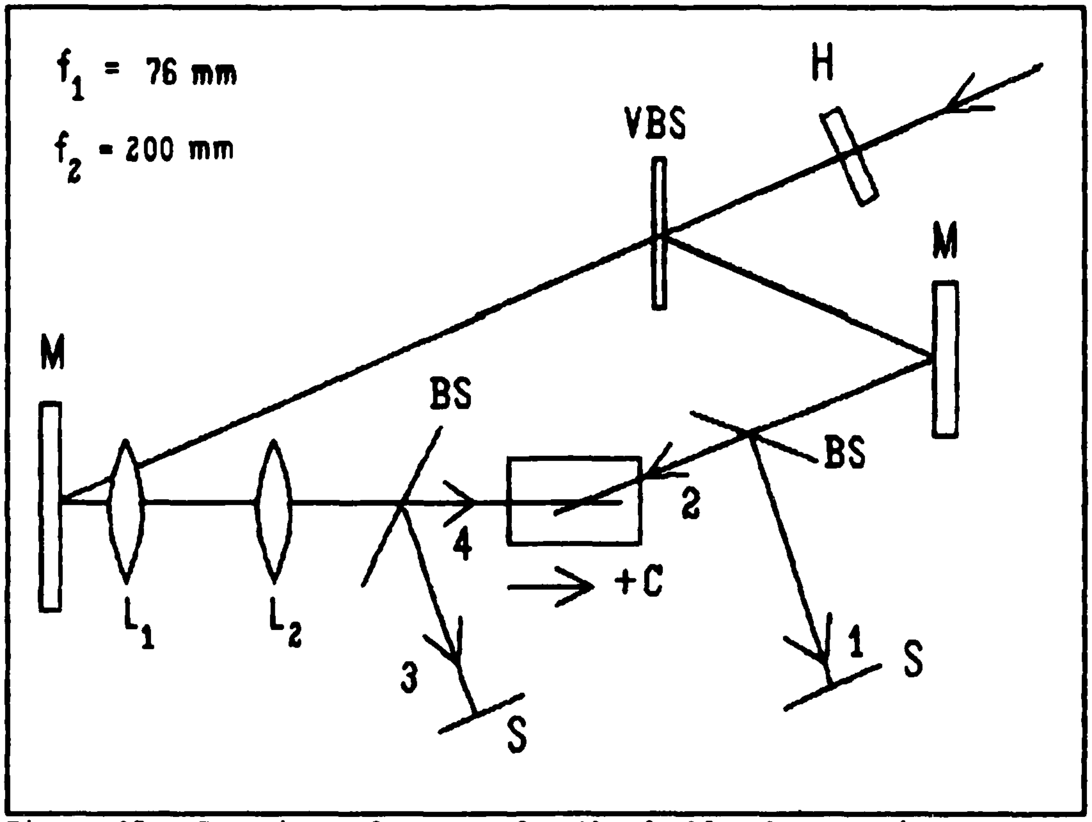

Figure 15. Experimental set-up for the double phase-conjugate mirror.

200 cm, making the beams mutually incoherent. (The measured coherence length of the laser was 14.5 cm for operation at 11.0 mW. The ILT laser was not available at the time this configuration was attempted.)

Initially the experimental parameters used in [25] were duplicated. Both beams were 1 mm in diameter and they crossed within the crystal at an angle of approximately 173°. This failed to produce any phase-conjugate return, so different crystal orientations, angles, and beam diameters were tried. There was still no phase conjugation, however. There is one possible explanation for this. Theoretically the minimum threshold coupling strength $\gamma\ell$ for the double phase-conjugate mirror is 2.0, while for self-pumping it is $\gamma\ell = 2.34$. Since self-pumping was demonstrated successfully, the problem must be the different crystal orientation and effective interaction length ℓ. During self-pumping the beam defines its own path within the crystal, optimizing both the length and direction of the beams to maximize the gain.

In the double phase-conjugate mirror configuration however, the orientation of the +C axis causes the coupling constant γ to be inherently smaller. γ is largest when the grating wave vector is not parallel to any of the crystal axes. During self-pumped phase conjugation the pumping loop is usually at an intermediate angle with respect to the +C axis, so that Φ has an intermediate value. In the double phase-conjugate mirror the writing beams are almost along the +C axis, so it is difficult to obtain a value for Φ much different than 90°.

Consider for example the calculated coupling constants for the beam geometries shown in Figure 16 listed tabulated in Table I. Case (A) is two-wave mixing, (B) is self-pumping, incoherent beam

coupling, or the bird-wing conjugator, and (C) is the double phase-conjugate mirror. The double phase-conjugate mirror has

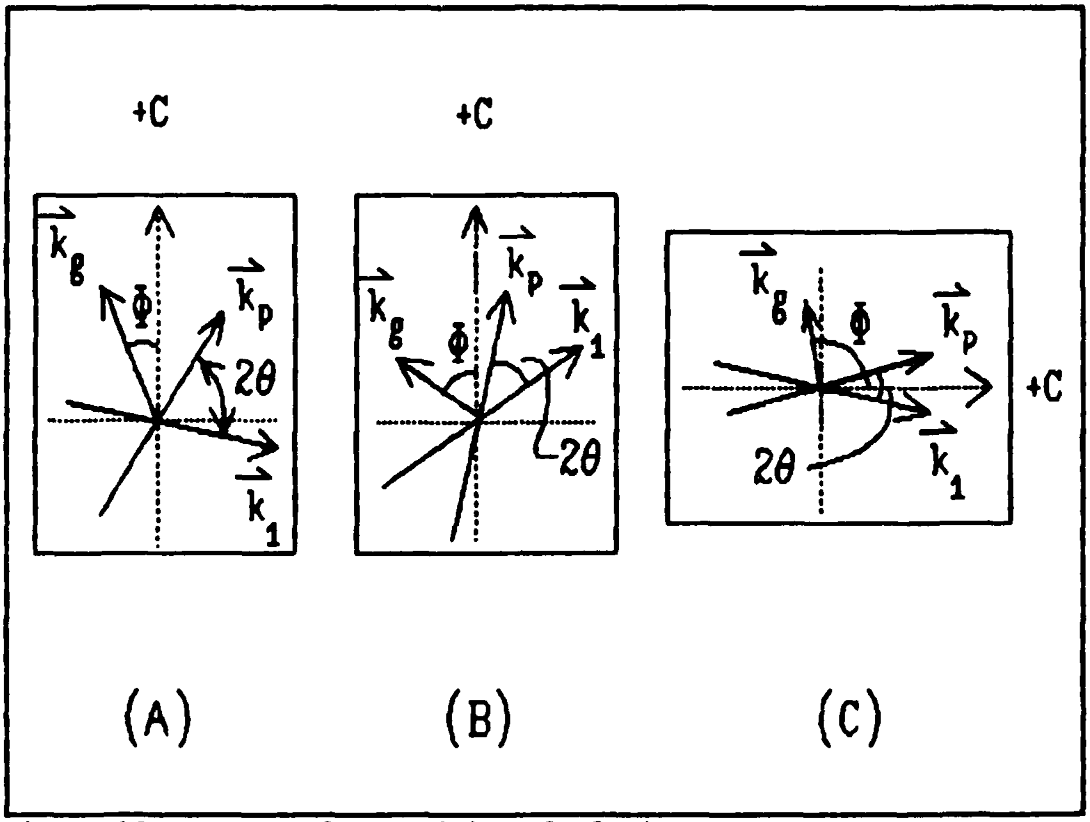

Figure 16. Beam angles used in calculating γ.

the smallest coupling constant over its range of input parameters. Thus, although the crystal sample is strong enough for self-pumped phase conjugation, it is not strong enough for use as a double phase-conjugate mirror.

TABLE I. Calculated Values for the Coupling Constant γ

Case	α	β	θ	ϕ	γ
A	94°	64°	15°	-11°	0.88
A	120	90	15	15	0.97
B	50	44	3	-43	2.19
B	35	29	3	-58	1.93
B	60	54	3	-33	1.97
C	5	-1	3	-88	0.14
C	11	-1	6	-85	0.23
C	41	-1	21	-70	0.32
C	81	-1	41	-50	0.41

(N_d is taken to be 3.0×10^{16} cm^{-3}).

(α and β of opposite sign indicates that the writing beams "straddle" the +C axis).

VII. The Mutually Incoherent Beam Coupler

The experimental set-up used to couple first two and then three mutually incoherent laser beams is shown in Figure 17. The optical path difference between beams 1 and 2 was approximately 517 cm, making them mutually incoherent.

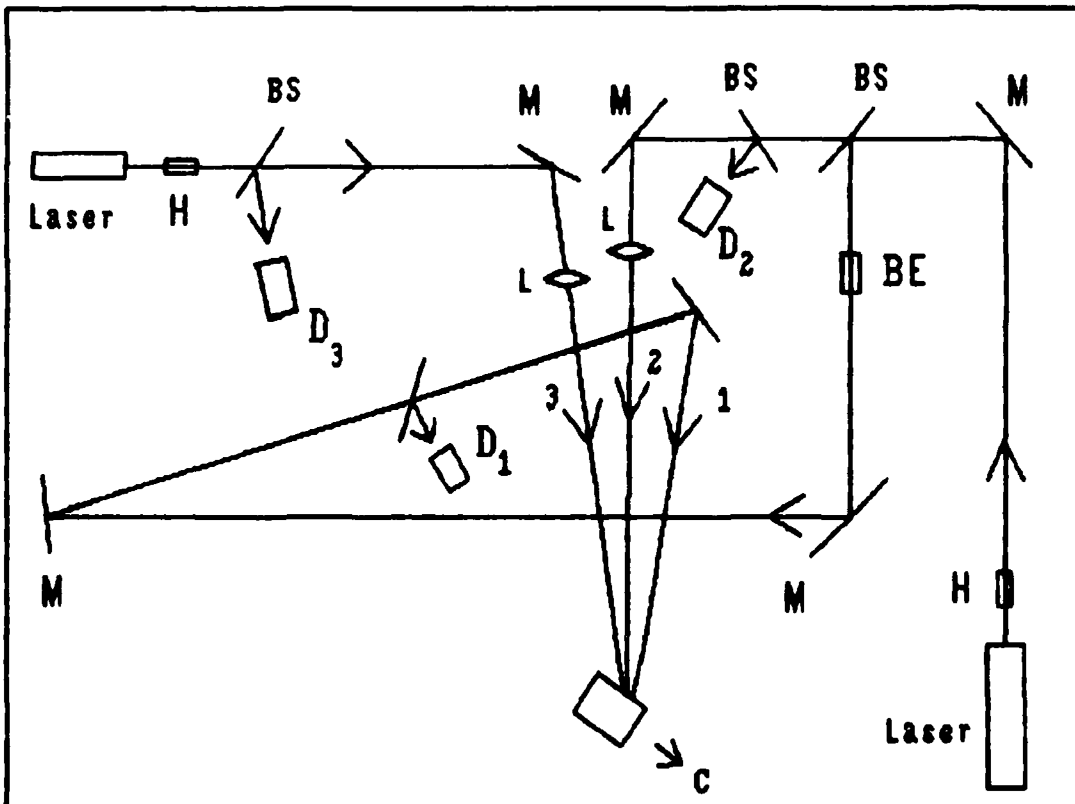

Figure 17. Experimental set-up for the mutually incoherent beam coupler. H: half-wave plate, BE: beam expander, M: mirror, BS: beam splitter, D: detector, L: lenses, f=500 mm.

Beam splitters were used to split the phase-conjugate returns from the incident beams. The reflectivities were found by taking the ratio of the phase-conjugate return split into the detector to that split into the detector when a 100% reflecting mirror was used in place of the crystal.

Coupling was verified by momentarily blocking each beam while observing the instantaneous change in reflectivities. A decrease in the reflectivity of the beam being blocked indicates some self-pumping; a decrease in reflectivity when one blocks one of the other beams indicates co-pumping into that beam. Stationary fringes were observed when the phase-conjugate returns were interfered with their respective pumping beams, as expected.

Two Input Beams

Mutual co-pumping was achieved using three different pairs of beams: (1) a pair from the Spectra-Physics laser, (2) a pair from the ILT laser, and (3) one beam from each laser. The results were the same in all three cases.

The angle between beams was kept between 2.5 and 6.5° and the crystal was rotated through different angles ϕ with respect to the normal to beam 2. The beam entrance locations were varied by translating the crystal in front of the beams. To maximize the index modulation the input beams were made equal in intensity. The intensities were 2.2 mW/cm^2 when only the Spectra-Physics laser was used; for the other two cases the intensities were 4.5 mW/cm^2.

Co-pumped phase-conjugate outputs were obtained for all angles of incidence ϕ greater than 50°, although the magnitude of the reflectivity was fairly sensitive to the translational position of the crystal, especially at lower angles of incidence. The co-pumped reflectivities ranged from 9 to 42%. The co-pumped phase-conjugate reflectivity was highly dependent on how well the beams reflected into each other at the

corner. Thus the easiest way to optimize the output is to vary the parameters while observing the beam paths as the coupling loop forms. Figures 18 and 19 illustrate the different coupling loops observed.

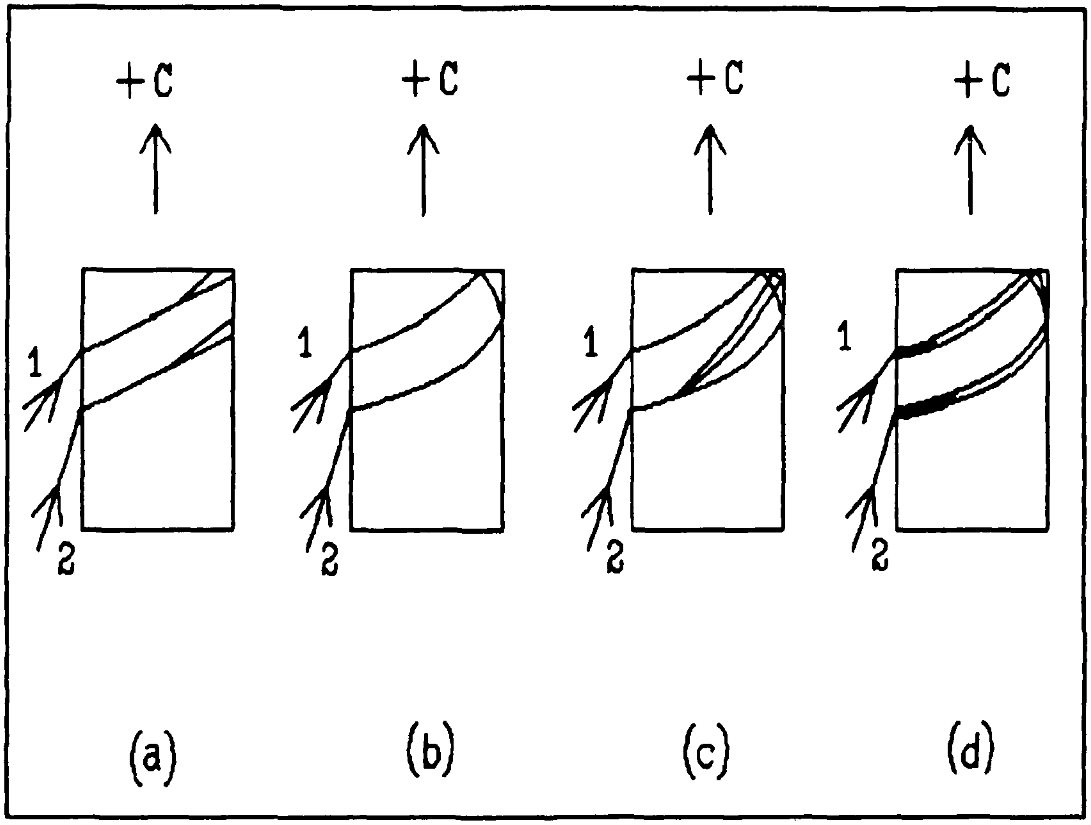

Figure 18. Two-beam mutual co-pumping loops. (a) The beams begin fanning into the loop. (b) The loop is formed. (c) Self-pumping also occurring. (d) Narrowing of the loop into two bands.

At times the loop narrowed into two very thin ($\approx$ 0.1 mm) bands where the edges of the single thick (1 mm) beam had been. This caused the reflectivity to jump, usually by at least 30%.

In addition to co-pumping each other, the beams self-pumped 0 to 100% of their phase-conjugate return. The reflectivity would also occasionally exhibit hysteresis upon blocking of the inputs. The ratio

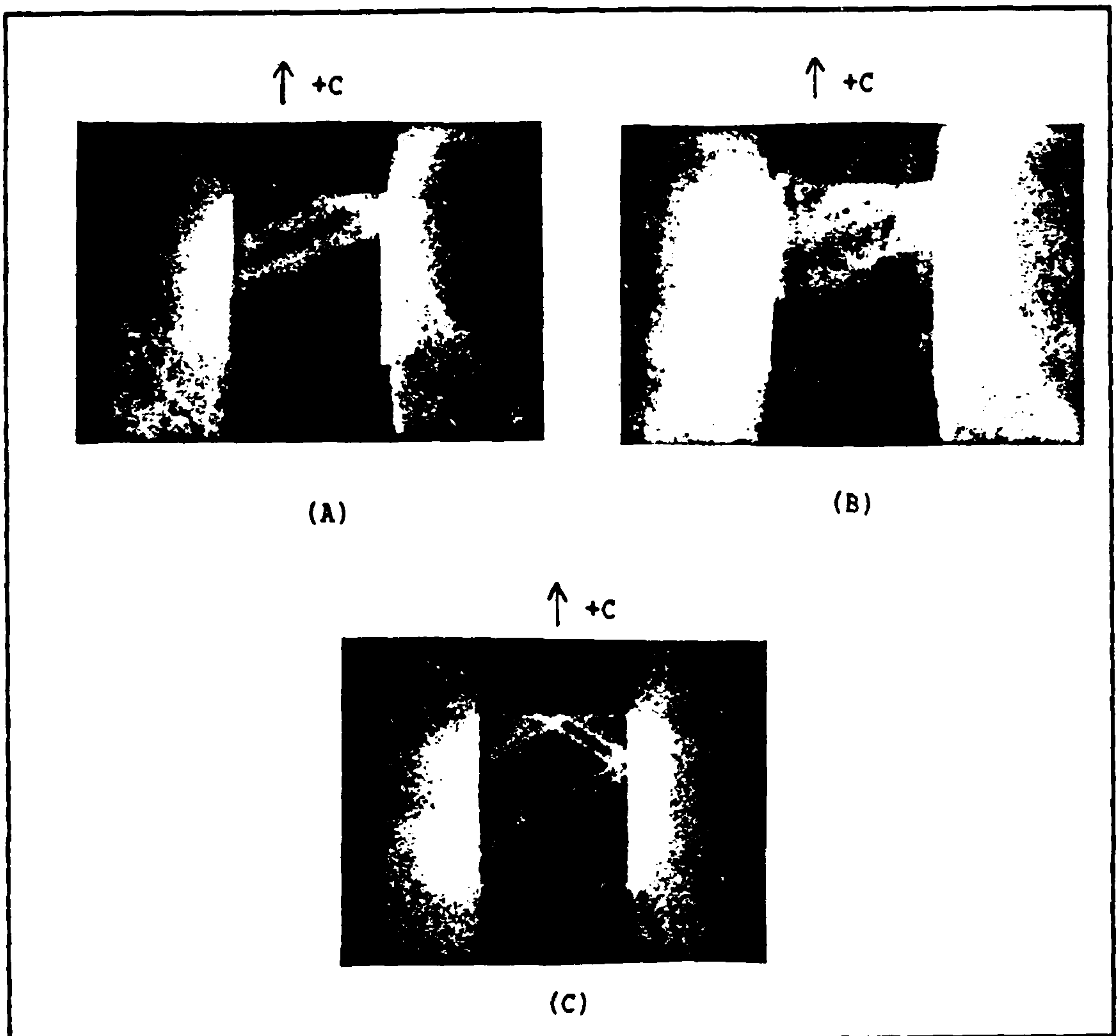

Figure 19. Photographs of two-beam co-pumping loops. (A) Without self-pumping, (B) with self-pumping, and (C) narrowing into two bands.

of self-pumping to co-pumping and the relative magnitudes of the two reflectivities could be changed by blocking and unblocking the beams. The beam height or degree of collimation may have been a factor influencing the degree of self-pumping. A less collimated beam might cause more fanning, allowing the formation of the additional self-pumping grating. It is also possible that one grating (self-pumping or co-pumping) can gain an advantage while the other beam is blocked. The

remaining beam reinforces the gratings it produces while erasing any other gratings.

The coupling loops shown in Figure 18 provide some evidence against the proposed ring cavity four-wave mixing mechanism, although there is no conclusive evidence for or against the two interaction region model. The observed angles of incidence at the coupling corner appeared to be too small to allow the formation of a simple ring cavity. Rather than straddling the opposite "entrance" corner (as in Figure 10(b)) both beams would return to the entrance face.

In addition, for a ring cavity mechanism moving interference fringes are expected since the oscillating pump beams are frequency shifted to satisfy the round-trip phase condition for the cavity. The phase-conjugate beams are then frequency shifted according to energy conservation of the nondegenerate four-wave mixing process. In this experiment, however, stationary fringes were observed during interference of each input with the conjugate it co-pumped. Thus, the phase conjugate was not frequency shifted and a ring cavity mechanism was not responsible for the phase conjugate output.

The separation of the loop into two very intense, narrow bands, which extend almost all the way back to the entrance face and which markedly increased the phase-conjugate reflectivity, seems to support a collinear mechanism similar to that described by Gower for the self-pumping geometry.

Three Input Beams

Coupling of three beams is qualitatively very similar to two-beam coupling, since the coupling seems to result from two different

co-pumping loops. Thus the discussion above concerning the four-wave mechanism for two-beam mutual co-pumping also applies to three-beam coupling. The three pumping configurations shown in Figure 20 produced three-beam coupling. Beams 1 and 2 were separated by 2.5°,

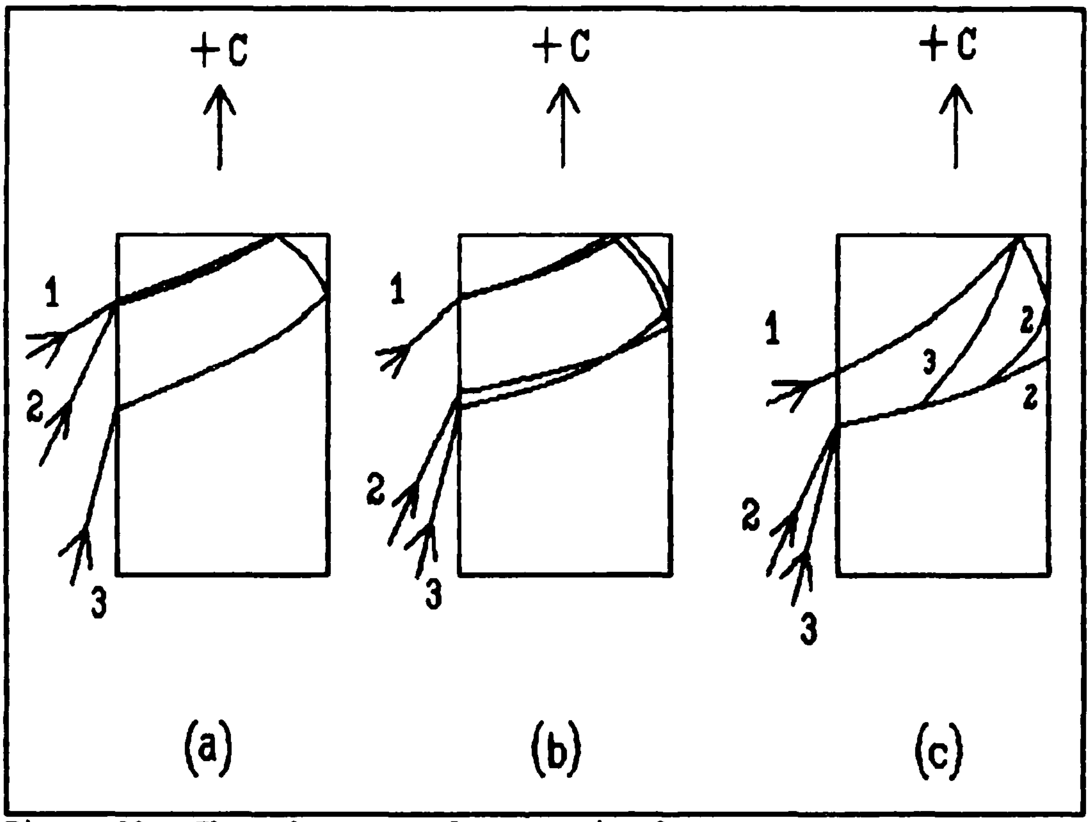

Figure 20. Three-beam mutual co-pumping loops.

beams 2 and 3 by 6°. Reflectivities ranged from 1 to 55% with the steady state reflectivities fluctuating by as much as 30%. One of the three phase-conjugate returnswas usually weaker (by about half) than the other two, although which beam would have a reduced reflectivity could not be predicted based on the beam geometry. The beams could not be coupled equally; one pair would co-pump the third and vice versus, but

co-pumping would not occur in both directions for all three beams. For example in 20(a) beams 1 and 2 co-pump 3 and 3 co-pumps 1 and 2; in 20(b) and (c) beams 2 and 3 co-pump 1 and vice versus. Self-pumping was only rarely observed; the beams were usually 100% co-pumped.

Optimization of the reflectivities visually was much more difficult for three inputs. For example, to couple as shown in Figure 20(b), beam 3 must be incident such that it couples with beam 1, but not such that it erases the 1-2 loop. This will occur for beam 3 located so that it fans into a position on the opposite face very close to, but not at the position of beam 2. This is achieved most easily for inputs which are nearly collinear.

Some representative reflectivities are listed below in Table II.

TABLE II. Measured Reflectivities During Three-Beam Coupling

Coupling Loop	R_1	R_2	R_3
(a)	10%	4%	6%
(a)	12-14	14-17	1-3
(a)	17-33	18-32	3-5
(a)	13	23-55	7
(b)	2-6	10-14	6-10
(c)	14	17-24	3

While coupling as shown in Figure 20(a) the fidelity of the phase-conjugate return for beam 1 was poor. The output beam diverged as it propagated away from the crystal. However, this output was due to the

four-wave mixing. The poor fidelity may have been due to the conical diffraction that can occur during four-wave mixing using internally reflected pumps, as discussed previously.

VIII. Conclusion

Mutually incoherent beam coupling of three input beams in $BaTiO_3$ was demonstrated using the mutually incoherent beam coupler configuration. The primary requirements on the input parameters were 1) that the beams fan into a +C corner and reflect into each other and 2) that the gratings formed be mutually consistent (i.e. such that they don't wash each other out). Equal co-pumping among the beams was not obtained; co-pumping in both directions between all three beam pairs did not occur.

Even for a given crystal sample it is difficult to generalize the input parameters (beam angles and entrance locations) which will result in three phase-conjugate returns, except to suggest that fairly large angles of incidence allow the beam to reflect into each other more efficiently. The increased beam fanning makes it more likely that part of the beam will be incident on the opposite crystal face at an appropriate coupling angle.

Since the phase-conjugate outputs were not frequency shifted with respect to their co-pumping beams it was determined that a ring cavity mechanism was not responsible for the phase conjugation reported here. The evidence for or against a two interaction region degenerate four-wave mixing mechanism was inconclusive. At times, however, the coupling loop collapsed into two intense, very narrow parallel bands which extended nearly to the entrance face. When this occurred the phase-conjugate reflectivity rose markedly (by approximately 30%). This observation supports a collinear four-wave mixing mechanism within each branch of the loop at those times.

Beam coupling was not achieved using the double phase-conjugate mirror configuration, even when only two input beams were used. This may have been due to the limited coupling strengths possible when the +C axis is used approximately parallel to the inputs. The threshold for coupling may not have been reached.

The phase-conjugate reflectivities achieved using the mutually incoherent beam coupler were somewhat low (1-55% for each beam). They did not noticeably perturb the source lasers' operation. Although the output beams themselves were coupled, it may be difficult to couple laser cavities (through their 96% reflectors) with such small returns. For a crystal strong enough to provide the threshold coupling strength the double phase-conjugate mirror may offer some improvement in reflectivity, since in that geometry the beams bend directly into one another, rather than around a loop.

Bibliography

1. Feinberg, Jack and G.D. Bacher. "Phase-Locking Lasers with Phase Conjugation", Applied Physics Letters, 48: 570-572 (3 March 1986).

2. Sternklar, S., S. Weiss, M. Segev, and B. Fischer. "Beam Coupling and Locking of Lasers Using Photorefractive Four-Wave Mixing," Optics Letters, 11: 528-530 (August 1986).

3. Kramer, Mark A., Sally Sifuentes, and Christopher M. Clayton. "Phase Locking of Ring Dye Lasers Using Incoherent Beam Coupling," Applied Optics, 27: 1371-1374 (15 April 1988).

4. White, J.O., G.C. Valley, and R.A. McFarlane. "Coherent Coupling of Pulsed Dye Lasers Using Nonlinear Phase Conjugation," Applied Physics Letters, 50: 880-882 (6 April 1987).

5. Pepper, D.M. and A. Yariv. "Optical Phase Conjugation Using Three-Wave and Four-Wave Mixing via Elastic Photon Scattering in Transparent Media," Optical Phase Conjugation, edited by R.A. Fischer. New York: Academic Press, 1983.

6. Yariv, Amnon and Pochi Yeh. Optical Waves in Crystals. New York: John Wiley & Sons, 1984.

7. Yariv, Amnon. "Phase-Conjugate Optics and Real-Time Holography," IEEE Journal of Quantum Electronics, 14: 650-660 (September 1978).

8. Pepper, David M. "Nonlinear Optical Phase Conjugation", Optical Engineering, 21: 155-183 (March/April 1982).

9. Cronin-Golomb, M., B. Fischer, J.O. White, and A. Yariv. "Theory and Applications of Four-Wave Mixing in Photorefractive Media," IEEE Journal of Quantum Electronics, 20: 12-30 (January 1984).

10. Kukhtarev, N.V., and T.I. Semenets. "Phase Conjugation by Reflection Gratings in Electrooptic Crystals," Applied Physics B, 41: 259-263 (1986).

11. Feinberg, Jack. "Optical Phase Conjugation in Photorefractive Materials," Optical Phase Conjugation, edited by R.A. Fischer. New York: Academic Press, 1983.

12. Fainman, Y., E. Klancnik, and Sing H. Lee. "Optimal Coherent Image Amplification by Two-Wave Coupling in Photorefractive $BaTiO_3$," Optical Engineering, 25: 228-234 (February 1986).

13. Klein, M.B. and G.C. Valley. "Beam Coupling in $BaTiO_3$ at 442 nm," Journal of Applied Physics, 57: 4901-4905 (1 June 1985).

14. Feinberg, Jack, D. Heiman, A. R. Tanguay, Jr., and R. W. Hellwarth. "Photorefractive Effects and Light-Induced Charge Migration in Barium Titanate," Journal of Applied Physics, 51: 1297-1305, (March 1980); Erratum, 52: 537 (January 1981).

15. Wemple, S.H., M. Didomenico, Jr. and I. Camlibel. "Dielectric and Optical Properties of Melt-Grown $BaTiO_3$," The Journal of Physics and Chemistry of Solids, 29: 1797-1803 (July 1968).

16. Weber, M.J., Ed. CRC Handbook of Laser Science and Technology Volume IV Optical Materials Part 2: Properties. Boca Raton, Florida: CRC Press, 1987.

17. Gunter, P. "Holography, Coherent Light Amplification and Optical Phase Conjugation with Photorefractive Materials," Physics Reports, 93: 199-299 (1982).

18. MacDonald, Kenneth R. and Jack Feinberg. "Theory of a Self-Pumped Phase Conjugator with Two Coupled Interaction Regions," Journal of the Optical Society of America, 73: 548-553 (May 1983).

19. Feinberg, Jack. "Asymmetric Self-Defocusing of an Optical Beam from the Photorefractive Effect," Journal of the Optical Society of America, 72: 46-51 (January 1982).

20. MacDonald, K.R. and J. Feinberg. "Enhanced Four-Wave Mixing by Use of Frequency-Shifted Optical Waves in Photorefractive $BaTiO_3$," Physical Review Letters, 55: 821-824 (August 1985).

21. Gower, M.C. and P. Hribek. "Mechanisms for Internally Self-Pumped Phase-Conjugate Emission from $BaTiO_3$ Crystals," Journal of the Optical Society of America B, 5, 1750-1757 (August 1988).

22. Chang, Tallis Y. and R.W. Hellwarth. "Optical Phase Conjugation by Backscattering in Barium Titanate," Optics Letters, 10: 408-410 (August 1985).

23. Lam, J.F. "Origin of Phase-Conjugate Waves in Self-Pumped Photorefractive Mirrors," Applied Physics Letters, 46: 909-911 (15 May 1985).

24. Yeh, Pochi, T.Y. Chang, and M.D. Ewbank. "Model for Mutually Pumped Phase Conjugation," Journal of the Optical Society of America B, 5: 1743-1749 (August 1988).

25. Weiss, S., S. Sternklar, and B. Fischer. "Double Phase-Conjugate Mirror: Analysis, Demonstration, and Applications," Optics Letters, 12: 114-116 (February 1987).

26. Sternklar, S. and B. Fischer. "Double-Color-Pumped Photorefractive Oscillator and Image Color Conversion," Optics Letters, 12: 711-713 (September 1987).

27. Ewbank, M. D. "Mechanism for Photorefractive Phase Conjugation Using Incoherent Beams," Optics Letters, 13: 47-59 (January 1988).

28. Smout, A.M.C. and R.W. Eason. "Analysis of Mutually Incoherent Beam Coupling in $BaTiO_3$," Optics Letters, 12: 498-500 (July 1987).

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The nonlinear crystal barium titanate was used to couple mutually incoherent argon-ion laser beams using a co-pumped four-wave mixing mechanism which transfers photons from each beam into the phase-conjugate outputs of the others. The four-wave mixing geometry which was used has been described in the literature as the "mutually incoherent beam coupler." The beams, all incident on the same crystal a face, form coupling loops as they internally reflect into each other at the opposite crystal corner. Coupling between two and three beams was investigated.

Coupling between two beams resulted in phase-conjugate returns which were both self-pumped and co-pumped. Reflectivities of 9% to 42% were obtained for all angles of incidence greater than 50 degrees. (The angle between beams was less than 7 degrees). The reflectivities were not reproducible. Apparently controlling the crystal orientation to within a half degree and the translational position to within 0.01 mm was not sufficient to guarantee the same beam paths within the crystal. Thus the dependence of the reflectivities on beam angles of incidence and input location could not be quantitatively described.

The reflectivity jumped by 30% when the coupling loop collapsed into two very intense, thin parallel beams running along the loop's inner and outer edges almost all the way back to the entrance face. This preferred state, which has not been reported elsewhere, was not always stable.

The reflectivities for three beam coupling ranged from 1% to 55% . The beams could not be equally coupled; one pair would co-pump the third and vice versa, but co-pumping would not occur in both directions for all three possible beam pairs. Although hysteresis was infrequently observed during two beam mutual co-pumping it was not observed when using three inputs.